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Investigating Feasibility of Drive-by Bridge Monitoring by Laboratory Experiments

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ABSTRACT: A potentially powerful drive-by bridge inspection approach was proposed to inspect bridge conditions utilizing the vibrations of a test vehicle while it passes over the target bridge. This approach suffers from the effect of roadway surface roughness and two solutions were proposed in previous studies: one is to subtract the responses of two vehicles (time-domain method) before spectral analysis and the other one is to subtract the spectrum of one vehicle from that of the other (frequency-domain method). Although the two methods were verified theoretically and numerically, their practical effectiveness is still an open question. Furthermore, whether the outcome spectra processed by those methods could be used to detect potential bridge damage is of our interests. In this study, a laboratory experiment was carried out with a test tractor-trailer system and a scaled bridge. It was observed that, first, for practical applications, it would be preferable to apply the frequency-domain method, avoiding the need to meet a strict requirement in synchronizing the responses of the two trailers in time domain; second, the statistical pattern of the processed spectra in a specific frequency band could be an effective anomaly indicator incorporated in drive-by inspection methods.

1 INTRODUCTION

Structural health monitoring based on modal parameters of bridge structures from vibration measurement has become a common idea for the condition assessment of bridges, since changes in structural integrity link to changes in modal parameters such as frequency, damping ratio and mode shapes (Farrar et al. 2001; Carden & Fanning 2004). A conventional way to identify bridge frequencies is utilizing vibration data measured directly from the bridge using vibration sensors mounted on the bridge. This conventional way generally requires the deployment and maintenance of the vibration sensors on bridges, which would be considered costly and time-consuming.

A complementary way is to utilize the vibrations of a test vehicle while it passes over the target bridge (Yang et al. 2004); this method is referred to as the drive-by bridge inspection (Kim et al. 2014). In the drive-by bridge inspection, however, the vehicle vibrations include the effect of roadway surface roughness, which makes it difficult to extract the bridge modal properties (Yang et al. 2012a).

To eliminate or reduce the effect of roadway surface roughness, two methods were proposed in previous studies. Both methods apply to a tractor-trailer system. One method is to subtract signals of two trailers towed by a tractor and then process the sub-

tracted signals with the fast Fourier transform and Wavelet transform to extract the bridge modal properties (Keenahan et al. 2014). Another way is to subtract the spectrum of one trailer from that of the other to obtain a residual spectrum (Yang et al. 2012a). Although those two methods were verified to be effective in previous theoretical and numerical studies, whether they are effective in practice is still an open question.

Furthermore, if the aforementioned two methods could reduce the effect of surface roughness, it would be of great interest whether the processed spectra could be used to detect damage in bridge. To be more specific, it is an interesting subject to examine whether damage in the test bridge would change the pattern of the frequency distribution in the processed spectrum and whether the change in this pattern of a candidate observation could indicate damage in the bridge.

In this study, a laboratory experiment was carried out to investigate the practical feasibility of drive-by inspection methods using a test tractor-trailer system. Specifically, the following two issues were investigated: 1) whether it is feasible to extract bridge frequencies aided by the above two methods to reduce the vibration components induced by roadway surface roughness; 2) whether the outcome spectra processed by the two methods can be used to detect potential bridge damage.

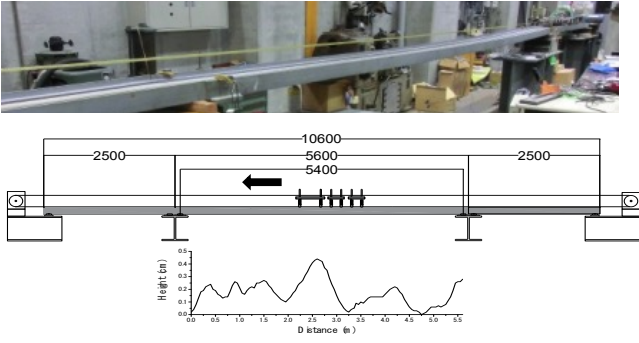


Figure 1. Scaled bridge model and surface roughness profile used in the laboratory experiment.

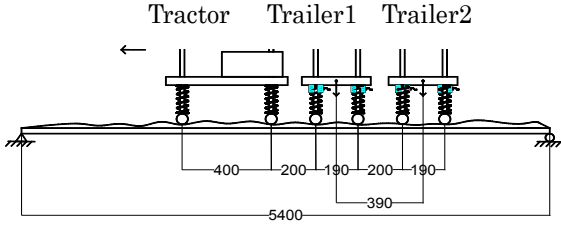


Figure 2. Tractor-trailer system and sensor layout (marked in blue) used in the laboratory experiment. (unit: mm)

Table 1 Bridge dynamic properties

1st natural frequency (Hz)	3.64
2nd natural frequency (Hz)	14.45
Damping constant	0.011

Table 2 Vehicle dynamic properties

	Tractor	Trailer
Total mass (kg)	19.67	6.70
Natural frequency of bounce on front axle (Hz)	3.52	2.49
Natural frequency of bounce on rear axle (Hz)	3.52	2.49

2 EXPERIMENT DESCRIPTION

2.1 Test Bridge

The experiment setup and roadway profiles considered in the experiment are shown in Figure 1. The scaled experiment bridge consisted of three spans of simply-supported beams: main target span at the center and accelerating and decelerating spans at two ends. The main span was a steel beam of 5.4 m in span length. It was equipped with a set of roadway profile that resembled real roadway profiles.

Uniaxial accelerometers were deployed at one-quarter, mid- and three-quarter spans to measure bridge's vertical acceleration responses. Dynamic properties of the beam were obtained from a preliminary free vibration experiment as shown in Table 1.

2.2 Test Vehicle System

The test vehicle system comprised three vehicles: one tractor and two trailers, as shown in Figure 2. The tractor was a two-axle vehicle, which serves to

excite the bridge into motion and thus plays the major role of an exciter to the bridge. The trailers were two-axle vehicles, which would be excited by the bridge that is already in vibration and thus majorly serve as receivers of the bridge vibrations. Two uniaxial accelerometers were mounted on each trailer: one on the front and the other on the rear axle, to measure the trailers' vertical vibrations. Those accelerometers were linked to a data logger installed on the tractor and the data logger was remotely controlled and monitored by a manual control panel through wireless transmission.

The two trailers were assembled with identical components and configurations so as to preferably behave with similar dynamic characteristics. Dynamic properties of the tractor and trailers were measured in an independent free vibration test and given in Table 2. For all measurements and all accelerometers, the sampling frequency was set as 100Hz. The vehicle speed was controlled by an external motor and kept constant. Three constant speeds were tested in this study: $S1 = 0.55$ m/s, $S2 = 1.05$ m/s, and $S3 = 1.77$ m/s.

2.3 Data Analysis

The acceleration responses of both trailers were recorded during their passage over the experiment bridge span. The Hanning window was used to remove the end discontinuity of measured data. For each trailer, the responses of the front and rear axles were averaged to remove pitching motions and to extract their pure bounce motions. Such processed acceleration response of the front trailer was denoted as $Acc1$ and that of the rear trailer as $Acc2$.

To reduce or eliminate the effect of surface roughness on the vehicle responses, two methods were proposed in previous studies. One was proposed by Keenahan et al. (2014) and was characterized as a time-domain method. First, synchronize the vibration responses ($Acc1$ and $Acc2$) of the two trailers with respect to the contact points. Next, subtract one of the synchronized responses from the other ($Acc1 - Acc2$). Then perform Fourier spectral analysis to the subtracted responses; let the Fourier spectrum of the subtracted response be denoted as $FT[Acc1 - Acc2]$. This method is referred to as the time-domain roughness-reduction method.

The other method to reduce or eliminate the effect of surface roughness was proposed by Yang et al. (2012a, b) and was characterized as frequency-domain method. First, take the Fourier spectra of both trailers' vibration responses; let their spectra be denoted as $FT[Acc1]$ and $FT[Acc2]$ respectively. Then, subtract one spectrum from the other, yielding a residual spectrum $FT[Acc1] - FT[Acc2]$. This method is referred to as frequency-domain roughness-reduction method.

Either $FT[Acc1-Acc2]$ by the time-domain method or $FT[Acc1]-FT[Acc2]$ by the frequency-domain method is expected to present bridge-related frequencies if the effect of surface roughness is successfully reduced or eliminated. The above two methods were tested with the laboratory moving-vehicle experiment and discussed in the next section.

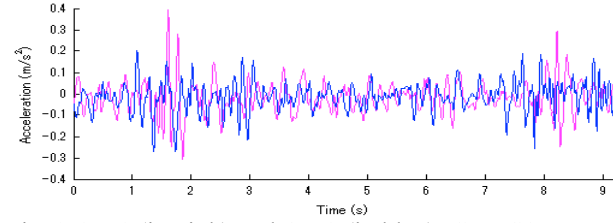


Fig. 3 Acc1 (in pink) and Acc2 (in blue), Case S1.

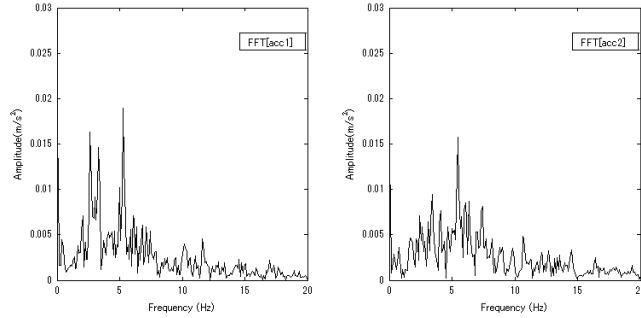


Fig. 4 $FT[Acc1]$ (left) and $FT[Acc2]$ (right), Case S1.

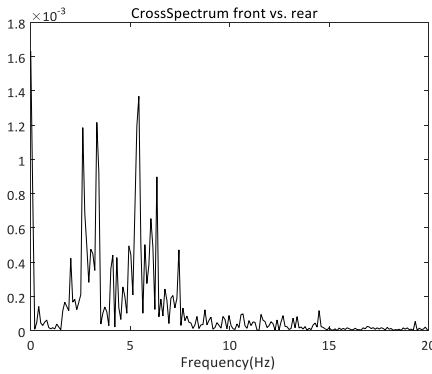


Fig. 5 Cross power spectral density of Acc1 & Acc2, Case S1.

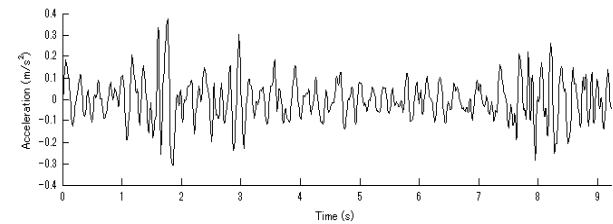


Fig. 6 Acc1-Acc2, Case S1.

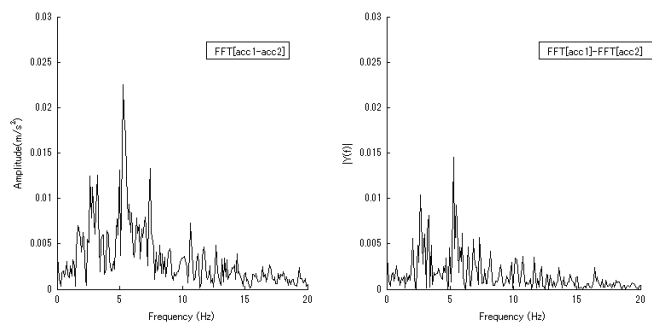


Fig. 7 $FT[Acc1-Acc2]$ (left) & $FT[Acc1]-FT[Acc2]$ (right), Case S1.

3 RESULTS AND DISCUSSIONS

3.1 Effectiveness of the Test Methods

Fig. 3 shows a set of typical Acc1 and Acc2 responses after synchronization, and Fig. 4 shows their Fourier spectra. The speed was $S1 = 0.55$ m/s so that it took about 9.5 s for the vehicle cross the bridge. From the Fourier spectrum of Acc1 ($FT[Acc1]$), three dominant frequencies were observed: 2.64Hz, which was close to trailer's bouncing frequency; 3.32Hz, which was close to bridge's first natural frequency that is a target frequency; 5.27 Hz, which might relate to surface roughness would be further clarified later. From the Fourier spectrum of Acc2 ($FT[Acc2]$), one dominant frequency was observed: 5.47 Hz, which might relate to surface roughness as also observed in $FT[Acc1]$.

What surprises was the presence of bridge-related frequency, despite a discrepancy of $3.64 - 3.32 = 0.32$ Hz. Actually $FT[Acc1]$ was already good enough for extracting bridge-related frequencies. It could support the idea of the drive-by method for extracting bridge frequencies. In contrast, the presence of the trailer's bouncing frequency in the trailer's responses was not surprising; essentially it is not our goal to find this frequency. As for the surface roughness-related frequency, it does not imply that the surface roughness consisted of single frequency component; there were many other components with smaller oscillatory amplitudes as can be observed in both $FT[Acc1]$ and $FT[Acc2]$. Those components unrelated to structural modes were the targets to be reduced or removed so as that the structural modes can be emphasized.

Fig. 5 shows the cross power spectrum density of Acc1 and Acc2, where similarly three dominant frequencies were identified: 2.62 Hz, which was close to trailer's bouncing frequency; 3.32 Hz, which was close to bridge's first natural frequency; 5.44 Hz, which might relate to surface roughness. What is encouraging is the bridge-related frequency remained in the cross power spectrum density, indicating that both trailers were excited by bridge vibrations during their passage, although this frequency was not yet clearly identifiable in $FT[Acc2]$. The presence of trailer's frequencies in the cross power spectrum density was expected, because the two trailers were designed to take identical dynamic properties. It is worthy of remarking that, if the two trailers were designed to take different dynamic properties, this trailer-related frequency might be absent in the cross power spectrum density. This remarking prediction is under investigations.

Let us investigate the feasibility of the proposed methods for reducing the effect of surface roughness by the aforementioned time-domain and frequency-domain methods. With the time-domain method,

subtracting Acc1 from Acc2 (see Fig. 6) and performing Fourier transform to the subtracted response yields the Fourier spectrum of the subtracted response $FT[Acc1-Acc2]$, as shown in Fig. 7. In contrast, subtracting the spectrum of one response from that of the other yields the residual spectrum $FT[Acc1]-FT[Acc2]$, as shown in Fig. 7.

In $FT[Acc1-Acc2]$, several dominant frequencies were observed, which also presented in $FT[Acc1]$ or $FT[Acc2]$: 2.64 Hz, which was close to trailer's bouncing frequency; 3.22 Hz, which was close to the bridge's first natural frequency; 5.28 Hz, which was considered again to relate to surface roughness. Unexpectedly the surface roughness-related components were little reduced. It is likely that the synchronization of the responses of the two trailers were hardly achieved in reality; more precisely speaking, the two trailers may not move to an exactly identical point in an identical travelling time. Besides the above three identified frequencies that also appeared in $FT[Acc1]$ and $FT[Acc2]$, a dominant frequency showed up around 7 Hz. This frequency component failed to relate to any known structural mode and therefore was considered as a spurious vibration mode introduced in the subtraction of two trailer's responses.

In $FT[Acc1]-FT[Acc2]$, three dominant frequencies were observed, which also presented in $FT[Acc1]$ or $FT[Acc2]$: 2.64 Hz, which was close to trailer's bouncing frequency as expected; 3.32 Hz, which is close to the bridge's first natural frequency; 5.28 Hz, which was regarded to relate to surface roughness. It was observed that the roughness-related components were slightly reduced and that little spurious vibration modes were introduced in the subtraction of two trailer's spectra. The bridge component was also slightly reduced but remained observable. The above observation demonstrated that $FT[Acc1]-FT[Acc2]$ would enhance drive-by inspections methods.

3.2 Effect of Speeds

It was discussed in previous studies that raising the moving speed of a test vehicle would negatively impact the successful extraction of bridge frequency by drive-by methods. The effect of moving speeds of the test vehicle was investigated with the tractor-trailers system herein. Besides the speed $S1 = 0.55$ m/s as tested in the previous section, the speed $S2 = 1.05$ m/s and $S3 = 1.77$ m/s were also considered.

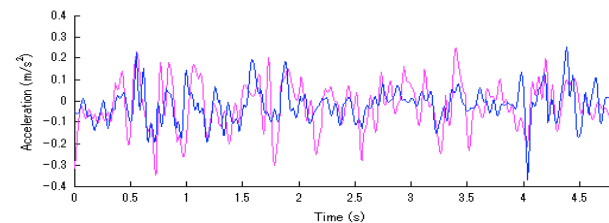


Fig. 8 Acc1 (in pink) and Acc2 (in blue), Case S2.

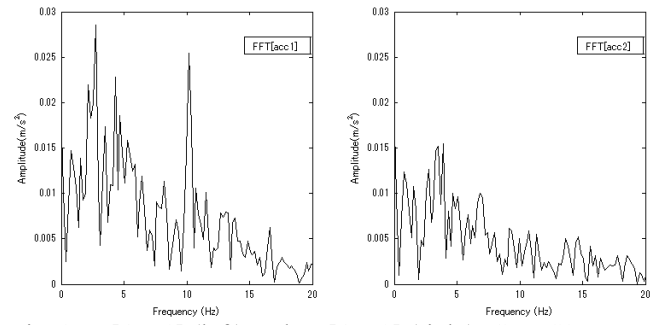


Fig. 9 $FT[Acc1]$ (left) and $FT[Acc2]$ (right), Case S2.

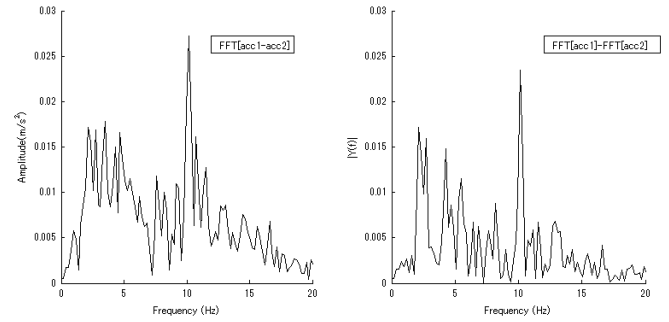


Fig. 10 $FT[Acc1-Acc2]$ (left) and $FT[Acc1]-FT[Acc2]$ (right), Case S2.

Raising the speed to S2 and performing the analysis following the same analysis procedure as above, one can get a set of typical synchronized vibration responses of the two trailers crossing the bridge as shown in Fig. 8. Their Fourier spectra $FT[Acc1]$ and $FT[Acc2]$ are shown in Fig. 9. Generally, to identify bridge frequency from those two individual spectra was relatively difficult, in comparison with those in S1 case. In $FT[Acc1]$, besides a dominant frequency close to the trailer frequency (around 2.5 Hz), a dominant frequency around 10 Hz was observed. Reminded that a dominant frequency appeared around 5 Hz in S1 case and approximately doubled as the speed doubled, this frequency component might closely relate to surface roughness. On the other hand, no obvious dominant frequency was observed in $FT[Acc2]$. However if one insisted to pick up some, a frequency band of 3 to 4 Hz would be a target, which would relate to bridge's first natural frequency of our interest.

Applying time-domain and frequency-domain roughness-reduction methods respectively yields $FT[Acc1-Acc2]$ and $FT[Acc1]-FT[Acc2]$, as shown in Fig. 10. First, it is observed that the roughness-related component of around 10 Hz was hardly reduced in $FT[Acc1-Acc2]$ but slightly reduced in $FT[Acc1]-FT[Acc2]$. Second, the bridge-related frequency did not stand out in $FT[Acc1-Acc2]$ but did in $FT[Acc1]-FT[Acc2]$, peaking around 4 Hz. It may indicate that $FT[Acc1]-FT[Acc2]$ would be more preferable than $FT[Acc1-Acc2]$ for the purpose of extracting bridge dynamic characteristics by drive-by methods.

When the moving speed was raised to S3, a set of typical synchronized vibration responses of the two trailers crossing the bridge can be obtained as in Fig. 11. Their Fourier spectra $FT[Acc1]$ and $FT[Acc2]$ are shown in Fig. 12. As expected, raising the speed greatly increased the difficulty in extracting bridge frequencies: no dominant frequency related to bridge frequency was observed in both $FT[Acc1]$ and $FT[Acc2]$. The only dominant frequency was around 2.8 Hz, which related to trailer's bouncing frequency without surprise.

Applying time-domain and frequency-domain roughness-reduction methods respectively leads to $FT[Acc1-Acc2]$ and $FT[Acc1]-FT[Acc2]$ shown in Fig. 13. In both spectra, the trailer-related frequency remained dominant and the other frequency components remained hardly identifiable. Based on this limited information, the evaluation of the effectiveness of $FT[Acc1-Acc2]$ and $FT[Acc1]-FT[Acc2]$ was unavailable. It is acknowledged that any roughness-reduction method would help little if the raw trailer responses carry little information about the bridge.

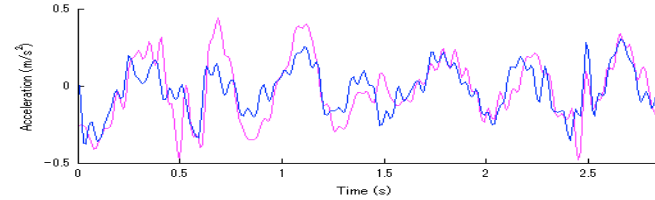


Fig. 11 Acc1 (in pink) and Acc2 (in blue), Case S3.

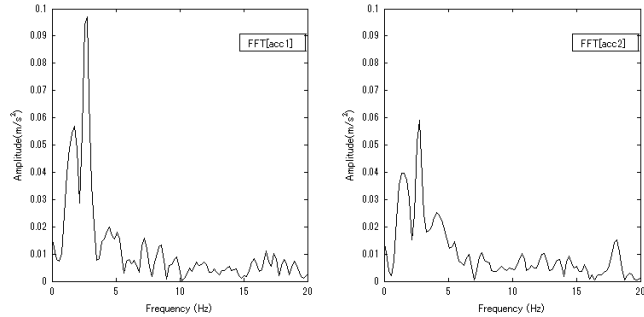


Fig. 12 $FT[Acc1]$ (left) and $FT[Acc2]$ (right), Case S3.

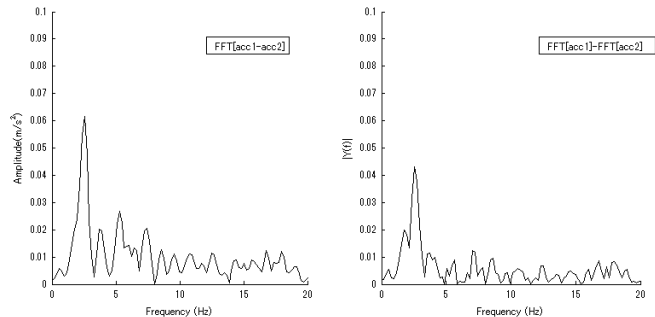


Fig. 13 $FT[Acc1-Acc2]$ (left) & $FT[Acc1]-FT[Acc2]$ (right), Case S3.

Table 3 Damage scenarios.

Scenario	mass (kg)	Exp f_{b1} (Hz)	Damping constant
INT	0	3.64	0.011
DMG1	8.3	3.50	0.009
DMG2	12.8	3.47	0.008
DMG3	17.2	3.42	0.007

4 ANOMALY DETECTION

The drive-by method for detecting anomalies in bridges was also tested. In this laboratory experimental study, to model bridge anomaly, several mass blocks were attached beneath the mid-span of the bridge. Four scenarios were considered: each with 0 kg (denoted as INT), 8.3 kg (DMG1), 12.8 kg (DMG2) and 17.2 kg (DMG3) of attached mass. The 1st natural frequency and the damping constant of the bridge for each scenario are summarized in Table 3. For each scenario, a number of runs of moving vehicle test were conducted and, for each run, the responses of the two trailers were taken and processed with the aforementioned time-domain or frequency-domain roughness-reduction methods. Herein the speed was kept in constant S2.

The anomaly in the test bridge may change the frequency distribution pattern in the processed Fourier spectrum $FT[Acc1-Acc2]$ or $FT[Acc1]-FT[Acc2]$. It follows that the change in the pattern of the frequency distribution of a candidate observation may indicate an anomaly in the bridge. Herein the pattern change was evaluated by Mahalanobis distance (MD), taking the Fourier amplitudes in a certain frequency band as variables and taking the observations from INT scenario as reference. 20 runs of test were conducted for INT scenario and 10 runs for DMG1, DMG2 and DMG3. Figures 14-17 show the MDs for $FT[Acc1-Acc2]$ and $FT[Acc1]-FT[Acc2]$, taking the amplitudes in the frequency band of 3.0 to 3.5 Hz and 3.5 to 4.0 Hz as variables respectively. Those two frequency bands were selected because the above preliminary tests revealed the band where the bridge's first natural frequency located. The mean of MDs was also calculated and plotted for each scenario.

It is observed that MDs for both $FT[Acc1]-FT[Acc2]$ and $FT[Acc1-Acc2]$ and both frequency bands showed noticeable change between the test scenarios, except for the DMG2 scenario in $FT[Acc1]-FT[Acc2]$ of 3.5 to 4.0 Hz band. Also, the MDs increased as anomaly level increased, implying that MDs could indicate not only the presence but also the level of bridge anomalies. Such observations are encouraging; they imply that the statistical pattern of the distribution of $FT[Acc1]-FT[Acc2]$ or $FT[Acc1-Acc2]$ could be a candidate in terms of the anomaly indicator incorporated in drive-by inspection methods.

5 CONCLUDING REMARKS

The feasibility of the drive-by inspection method using two trailers was investigated through laboratory experiments. Several concluding remarks can be drawn as follows.

1) For practical applications, it would be preferable and helpful to apply frequency-domain roughness-reduction method, i.e. to subtract the spectrum of one trailer from that of the other to yield a residual spectrum $FT[Acc1]-FT[Acc2]$. It may not need to meet a strict requirement in accurately synchronizing the responses of the two trailers in time domain, while the time-domain method may need.

2) Raising the moving speed of a test vehicle would negatively impact the successful extraction of bridge frequencies by drive-by methods, which supported the observations in previous studies. It is acknowledged that, if the raw trailer responses carry little information about the test bridge, any roughness-reduction method would help little.

3) The statistical pattern of the residual spectrum $FT[Acc1]-FT[Acc2]$ or the spectrum of the subtracted response $FT[Acc1-Acc2]$ could be an effective anomaly indicator incorporated in drive-by inspection methods. Taking observations from the intact case as reference and taking the Fourier amplitude in a certain frequency band as variables, the Mahalanobis distance (MD) of a candidate observation could indicate the presence and the relative level of anomaly.

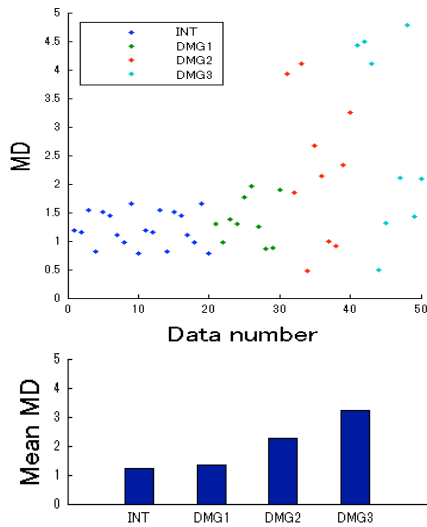


Fig. 14 MD for $FT[Acc1-Acc2]$, 3.0 to 3.5 Hz.

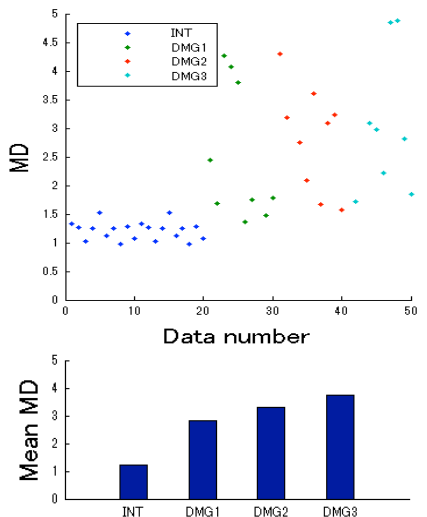


Fig. 15 MD for $FT[Acc1]-FT[Acc2]$, 3.0 to 3.5 Hz.

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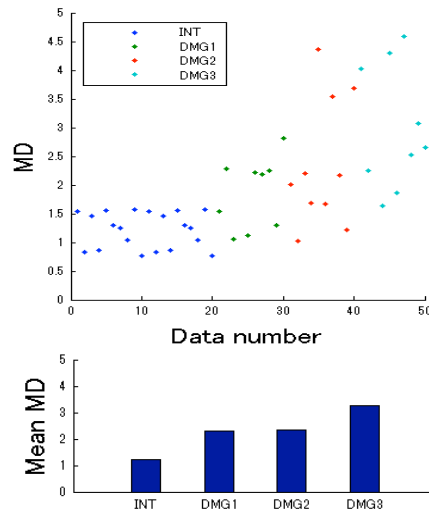


Fig. 16 MD for $FT[Acc1-Acc2]$, 3.5 to 4.0 Hz.

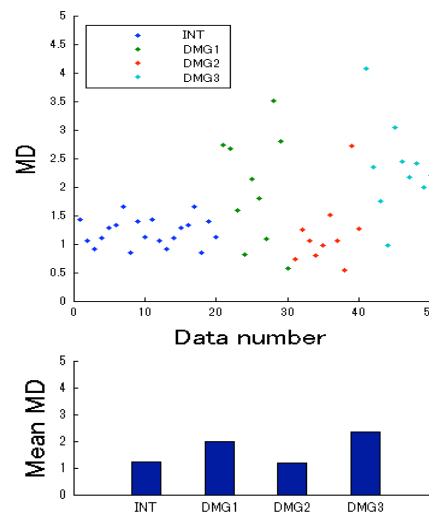


Fig. 17 MD for $FT[Acc1]-FT[Acc2]$, 3.5Hz to 4.0Hz.